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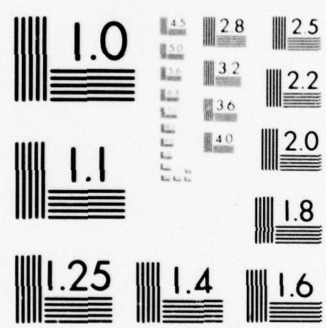

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SUBMERSIBLE EXPLORATION OF GUAYMAS BASIN: A PRELIMINARY REPORT OF THE GULF OF CALIFORNIA 1977 OPERATIONS OF DSV-4 Seacliff

Peter Lonsdale

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A diving program with DSV-4 Seacliff examined the submarine geology of Guaymas Basin, a young and growing basin in the Gulf of California. Four dives in the axial rift valleys allowed observation of fresh normal fault scarps that were oriented parallel and orthogonal to the direction of relative plate motion; established that the major peaks within the axial rift valleys were sedimentary horsts and discovered and sampled extensive sinter terraces of talc and metal sulfides, built around hydrothermal vents. Two dives across the southeast transform fault found no fresh fault scarps on sediment slopes that were (over)

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SUBMERSIBLE EXPLORATION OF GUAYMAS BASIN: A PRELIMINARY REPORT OF THE GULF OF CALIFORNIA 1977 OPERATIONS OF DSV-4 Seacliff

Peter Lonsdale

ABSTRACT

A diving program with DSV-4 Seacliff examined the submarine geology of Guaymas Basin, a young and growing basin in the Gulf of California. Four dives in the axial rift valleys allowed observation and photography of semi-lithified layered diatomite cut by fresh normal fault scarps that were oriented parallel and orthogonal to the direction of relative plate motion; established that the major peaks within the axial rift valleys were sedimentary horsts rather than volcanic constructions; and discovered and sampled extensive sinter terraces of talc and metal sulfides, built around hydrothermal vents that were densely populated with molluscs. Two dives across the seismically active southeast transform fault found no fresh fault scarps on sediment slopes that were efficiently tilled by a very dense benthic fauna, but encountered extensive ledges and glide blocks of clastic rocks that are believed to be outcrops of old "proto-gulf" sediments on the basin margins. Two dives on the insular slope of Isla Tortuga photographed and sampled flow fronts of fresh pillow and tubular basalt that marked submarine flank eruptions from this young volcano.

INTRODUCTION

During November 1977 the U.S. Navy submersible DSV-4 Seacliff made 8 dives to depths of 1-2 km within Guaymas Basin, in the central Gulf of California. The main aims were close-up visual observation of deep-sea geomorphology at the seismically active boundary between the Pacific and North American plates, and sampling of any rock outcrops exposed there. This information will be used to make inferences about the magnitude and frequency of tectonic, volcanic and hydrothermal processes along plate boundaries in Guaymas Basin, and to compare the distinctive structures of Gulf of California spreading axes and transform faults with those on mid-ocean rises that have recently been examined with near-bottom techniques.

This initial report was prepared before all of the sea-floor photographs have been processed or analyses of the rock samples have been completed. It presents a narrative of the entire expedition of which the dives in Guaymas Basin were the successful part, summaries of each dive, and some preliminary interpretations that allow the significance of the results to be assessed.

NARRATIVE OF Seacliff's 1977 GULF OF CALIFORNIA EXPEDITION

Seacliff was carried to the dive sites aboard its tender M/V Maxine D, a 50 m oil-rig supply vessel, and was launched and recovered by a mobile crane parked on the ship's fantail. M/V Maxine D also provided accomodation and lab space for the diving and support crews of the submersible and for the two-man scientific parties. The ship and submersible left their San Diego base at 1600L November 1 and returned at 1900L December 6. This 35 day deployment was planned as a four-leg expedition, with intermediate port stops at Guaymas and Mazatlan; because of operational problems Leg 2 was interrupted by two unscheduled additional stops in Guaymas, and the ship visited La Paz instead of Mazatlan.

Leg 1, San Diego - Guaymas, November 1 - November 8, had P. Lonsdale and S. Bloomer (both of Scripps Institution of

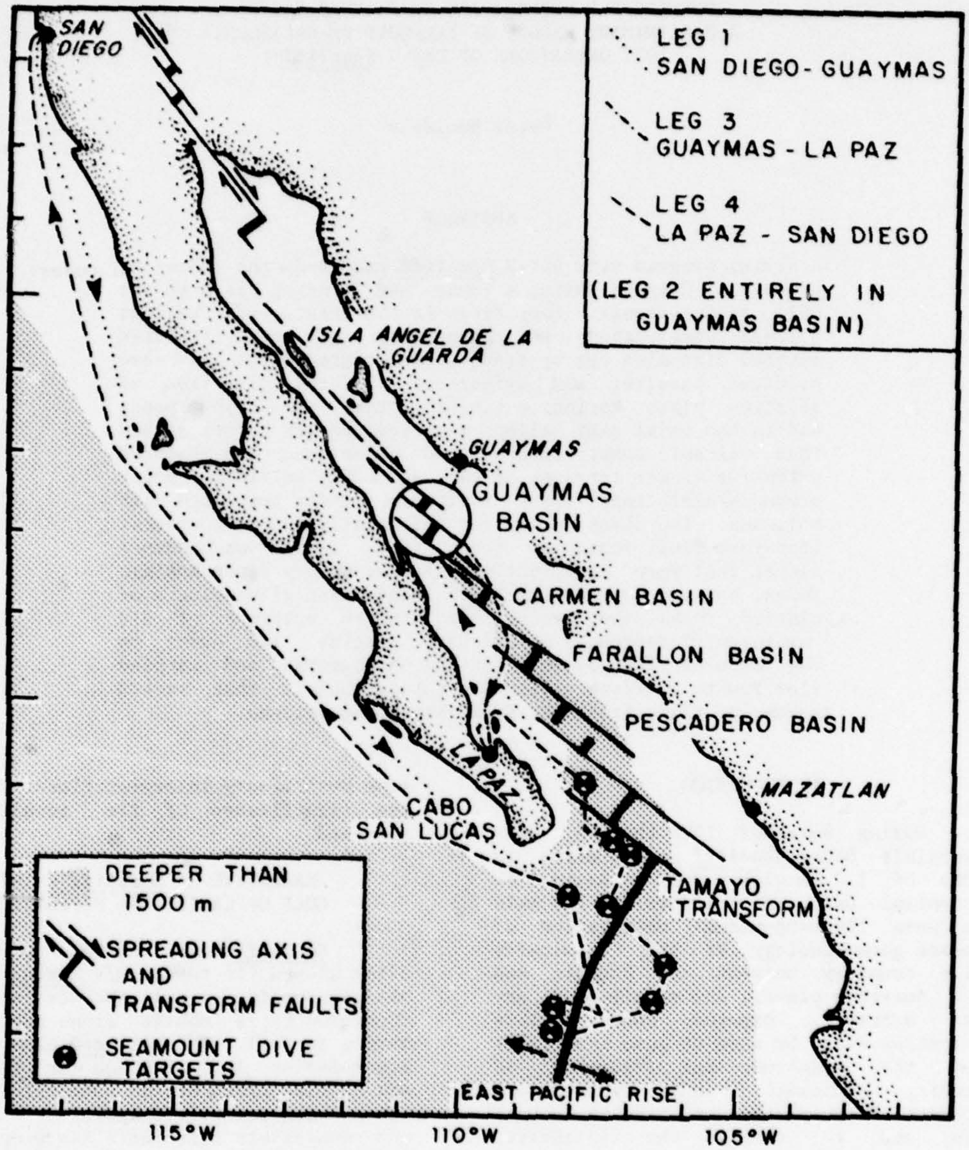

Fig. 1. Track of the expedition.

Oceanography) as scientific observers. The plan was to steam beyond the southern tip of Baja California and dive on the summits of young seamounts near the crest of the East Pacific Rise, before running north up the Gulf for one or two dives in Guaymas Basin. However, when the components of M/V Maxine D's echo-sounding system were connected as we steamed down the west coast of Baja California, it became clear that the hull-mounted 12 kHz transducer was not operational. Lacking any capability to echo-sound, we judged that it would be difficult to find and usefully explore the small areas of the seamounts' summits that rise above Seacliff's maximum operating depth, and decided to postpone our effort at these sites until the transducer had been replaced. This decision was reluctantly arrived at in view of the perfect diving conditions (a flat sea and no wind) that prevailed as we rounded Cabo San Lucas; these conditions encouraged us to attempt a dive on the ridge or chain of seamounts that extends along the southwest side of the Tamayo transform fault, even though our bathymetric charts of this area were known to be imprecise, and the site was (just) beyond radar range of the coast. As Seacliff was descending, a rare satellite fix indicated that the launch site was on the southwest flank of the ridge, and although the submersible travelled toward the supposed postion of the summit for about 8 km at a depth of 1900 m, its batteries were exhausted before we could reach sea floor that rose above our maximum operating depth, and Seacliff surfaced after 7 frustrating hours without seeing the bottom. The dive was used for a thorough check-out of the submersible's systems. We then proceeded to the well charted Guaymas Basin, where Dive 302 was successfully made on its southwest margin, well within radar range of land. Increasingly rough seas that had complicated the recovery after Dive 302 dictated that Dive 303 be close in to the lee of Isla Tortuga, a target of secondary importance.

Leg 2, Guaymas - Guaymas, November 11 - November 21 had P. Lonsdale and L. A. Lawver (Scripps Institution of Oceanography) as scientific observers. Maxine D left port with a new, towed, 12 kHz tranducer, borrowed from Scripps and delivered overland. The seas were still too rough for safe submersible recovery in the open waters of the central Guaymas Basin, so Dive 304 was also made in the lee of Tortuga. The CTFM sonar worked very poorly during Dive 304, though this did not seriously impair the dive. Post-dive trouble-shooting revealed that there had been a salt water leak into a major electrical connector. Although weather conditions had improved enough to allow diving at exposed sites, we were compelled to return to Guaymas to await delivery of a replacement cable; during our enforced stay the 12 kHz transducer was fitted into the sonar dome, making a quieter and, we hoped, more permanent installation. After the repairs had been made, 5 productive dives in Guaymas Basin (Dives 305, 306, 308, 309 and 310) were made in quick succession, interrupted only by a brief, shallow certification dive without a scientific observer (Dive 307) and a short stop in Guaymas on November 18 to allow the certifying officer to disembark.

Leg 3, Guaymas - La Paz, November 22 - November 26, had D. Fornari (Lamont-Doherty Geological Observatory) and R. Batiza (Washington University) as scientific observers. The plan was to use 3-4 days to complete the Guaymas Basin work, diving on a volcanic pinnacle in the northwestern part of the basin (Fig. 2), a hydrothermal field discovered in the northern rift valley on Leg 2, and a site in the southern rift valley with high conductive heat flow which is a candidate for IPOD deep-sea drilling. The ship was then to steam down the Gulf, with several dives on the seamount chain near the Tamayo transform fault before a scheduled November 30 arrival in Mazatlan. However on leaving the shelter of Guaymas harbor the northwest wind was found to be so strong (30-40 km/hr) and the waves so high (>2 m) that the lee of Isla Tortuga seemed to be the only plausible dive site. By the time Maxine D arrived there the wind had freshened to a whole gale, gusting to 100 km/hr. Launch and recovery of the submarine, even close in to the island, was out of the question; the ship anchored off Tortuga to ride out the gale, unable to leave the island's shelter because of fears that green water washing over the fantail would damage the submersible. A party did go ashore, sampling rocks to supplement Batiza's extensive collection from this young volcanic island. After 3 days the gale moderated enough to allow Maxine D to leave the shelter of Tortuga in safety, and it proceeded down the Gulf, with a high following sea, in the hope of finding better weather at the planned dive sites off Mazatlan. However, half-way there a serious fire occurred in the engine room, requiring shut-down of one engine and a diversion to the nearest port, La Paz, for repairs. Attempting to enter La Paz at dawn on November 26, Maxine D ran aground on the sand bar that protects the harbor. Although the vessel was soon refloated, the sonar dome containing the underwater communications equipment and the newly-installed 12 kHz transducer had been sheared off and destroyed.

Leg 4, La Paz - La Paz, December 1 - December 6, had D. Fornari and P. Lonsdale as scientific observers. Departure was delayed by the need to repair or replace the engines and sonars with parts air-freighted from the United States. When we did steam out, it was into a strong northwest breeze (40 km/hr) and rough seas (2-3 m). As we went south, visiting in turn each potential dive site on young East Pacific Rise seamounts, the wind abated somewhat but the waves and swell increased, presumably because of the increased fetch. This was all the more galling because there had been perfect diving weather here earlier, during Leg 1. After spending a day drifting over seamounts near the rise crest at 21°N, watching the waves increase as the northwest wind persisted, we abandoned hope of further dives and, lacking any of the necessary clearances for work in sheltered sites of secondary interest close to land, we headed back to San Diego. Throughout the return transit we pitched into moderate waves and swell.

In summary, Seacliff's diving operations were hampered on Leg 1 by lack of a working echo-sounding system on its support ship, abbreviated on Leg 2 by failure of one of its electrical connectors, and crippled on Legs 3 and 4 by a combination of mechanical breakdowns of the ship, accidents and, especially, unseasonably bad weather. Strong northwest winds are characteristic of the lower Gulf only from late December through March, and seldom persist for more than 2-3 days. Good weather and a fully operational condition of the ship and submersible coincided for several days on Leg 2, and most of the rest of this report is concerned with the successful dives during that period, in Guaymas Basin.

GUAYMAS BASIN: A SUMMARY OF PREVIOUS KNOWLEDGE

The deep basins of the Gulf of California have been created by sea-floor spreading at an extension of the East Pacific Rise that was initiated about 4-5 m.y.b.p., when the Pacific-North American plate boundary jumped inland, and Baja California began to raft away from North America (Atwater, 1970; Larson, 1972). Parts of the present Gulf, including the flanks of Guaymas Basin, had previously been occupied by a narrow "proto-Gulf" in which silts and sands were deposited at moderate depths (Moore, 1973). Throughout the Gulf, accretion of oceanic crust seems to occur along short segments of spreading axis that are connected by long transform faults, many of which bound continental crust. In the northern Gulf and Imperial Valley, spreading axes are ill-defined because of deep burial by rapid deposition of Colorado River sediments (Elders et al., 1972; Henyey and Bischoff, 1973); in Guaymas Basin and the other, deeper, basins further south, northeast-trending fault troughs that are believed to be axial rift valleys have been interpreted as the loci of active spreading (Moore, 1973; Bischoff and Henyey, 1974; Sharman, 1976). However, these spreading axes lack certain features of typical mid-ocean spreading centers: no identifiable sequences of magnetic anomalies are disposed about them, and the assumed centers of spreading have significant blankets of sediment, which do not thicken regularly with increasing distance from the axes. These distinctive features have been related to the youth of the basins, which may engender frequent jumping of the plate boundary as the system evolves to a stable configuration. It also ensures rapid deposition of terrigenous sediments (partly from turbidity currents) which may inhibit localized extrusion of basalt.

Guaymas Basin (Fig. 2) has an en echelon pair of axial rift valleys, oriented 040°, 3-4 km wide and up to 200 m deep. These troughs are offset 20 km, and presumably connected by a transform fault within the basin, though there is scant evidence for any such structure in the bathymetry, seismic profiles or microseismicity. Long, seismically active transform faults connect the landward ends of the northern and southern troughs with short spreading axes in San Pedro Martir and Carmen Basins, respectively; along most of their lengths these transform fault zones separate oceanic from continental crust.

There is a cover of over 1 km of unconsolidated sediment in parts of Guaymas Basin, and even the floors of the axial rift valleys, assumed to be the youngest region of the basin, commonly have a fill of 200-300 m. On seismic reflection profiles the only outcrops or near-outcrops of volcanic basement, with the exception of Isla Tortuga on a fracture zone extension of the central transform fault, seem to be at a small volcanic pinnacle that projects through the sediment blanket near 27°22'N 111°36'W, and near the foot of the northwest wall of part of the northern trough. In addition, several small peaks and ridges that rise above the floors of the axial rift valleys have been interpreted as volcanic constructions (e.g., Bischoff and Henyey, 1974). Despite the rapid influx of terrigenous sediment, deposition in Guaymas Basin at present is primarily pelagic, with over 50% (by weight) of the recent sediment being opal tests derived from profuse blooms of diatoms in the productive overlying waters (Calvert, 1966). On the sides of the

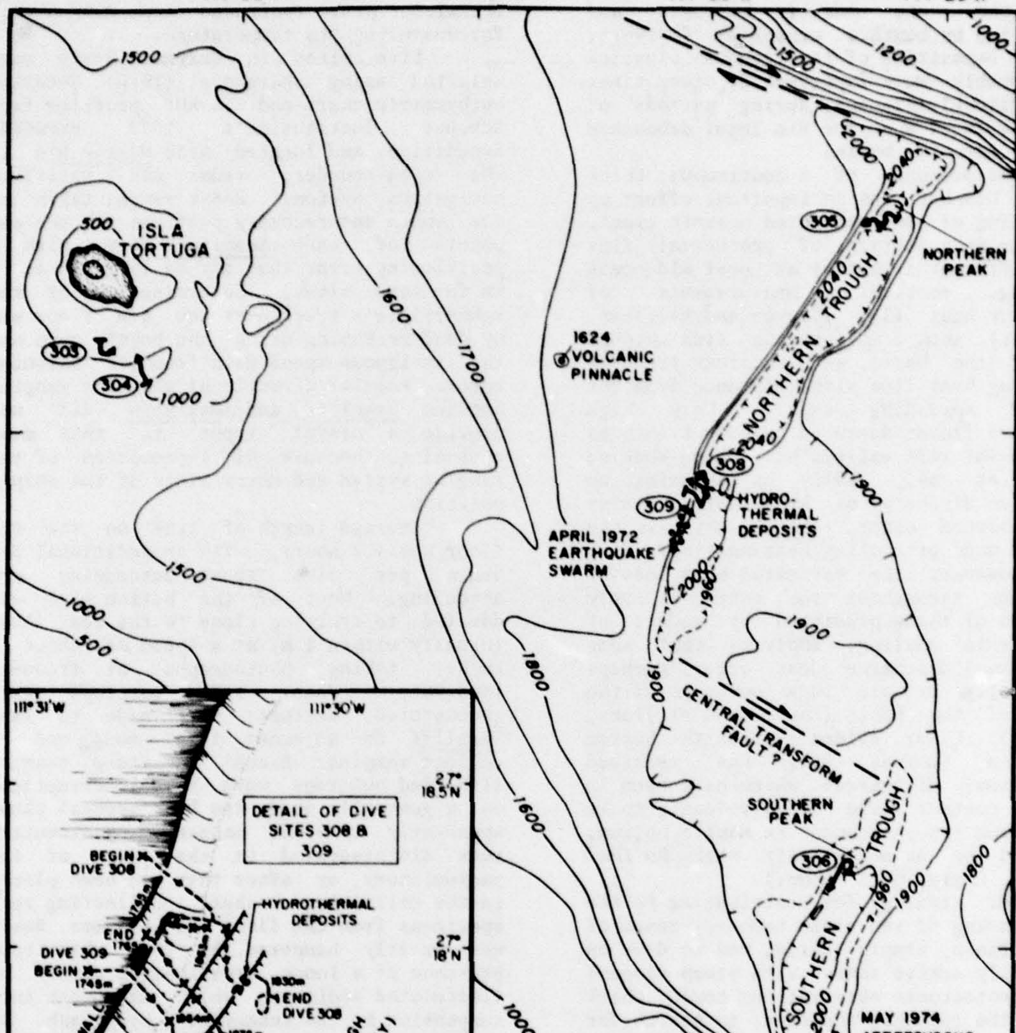

Fig. 2. Dive sites in Guaymas Basin. Bathymetry is from Sharman (1976) and, around Isla Tortuga, after Batiza (in press). Earthquake epicenters are from Reichle (1975). Inset showing approximate routes of Dives 308 and 309 has spot depths in meters, as measured by Seacliff's pressure gauge; fault scarps are shown schematically.

basin these diatomaceous sediments have accumulated beneath oxygen-deficient bottom water, and are laminated, but on the basin floor they are heavily burrowed and homogenized by benthic organisms (Calvert, 1964). Deposition of terrigenous clastics was probably more important at other times in the Plio-Pleistocene, during periods of lower sea-level when the Rio Yaqui debouched directly into the basin.

The presence of a continuous, thick sediment blanket has an important effect on the cooling of newly accreted oceanic crust, resulting in a pattern of geothermal flux quite different from that at most mid-ocean spreading centers. Measurements of conductive heat flow (Lawver and Williams, in press) show a uniform high flux through most of the basin, with no clear trend of decreasing heat flow with distance from the presumed spreading axes. Very high conductive fluxes measured on some transects of the axial rift valleys have been modeled (Lawver et al., 1975) by assuming no convective discharge of hydrothermal fluids to the bottom water, though this is the dominant mode of cooling near most spreading axes. However, the estimated heat loss by conduction throughout the basin is only about 50% of that predicted by models of lithospheric cooling, implying that some hydrothermal discharge does occur, perhaps episodically or via rock outcrops at the margins of the basin (Lawver and Williams, in press). Clear evidence that the bottom water in Guaymas Basin has received hydrothermal discharges which have been in intimate contact with fresh volcanic rocks comes from its enrichment in mantle helium, signified by an anomalously high He^3/He^4 ratio (H. Craig, pers. comm.).

Our strategy for contributing to the understanding of the plate boundary zones of Guaymas Basin, simply stated, was to dive on seismically active zones with steep slopes, where neotectonic observations could check some of the tectonic theories; to search for basement outcrops; and to follow up any hint of hydrothermal discharge.

STYLE OF OPERATION OF THE SUBMERSIBLE

DSV-4 Seacliff, operated by the U.S. Navy's Submarine Development Group One, is an 8 m long sister ship of DSRV Alvin, with a complement of three (pilot, co-pilot and observer) and a maximum operating depth of 1980 m (6500 feet). During operations in the Gulf of California the submersible was equipped with two hydraulic manipulator arms, a 70 mm Hydroproducts camera, hand-held 35 mm single lens reflex and 8 mm movie cameras (photographing through the observer's viewport), a CTFM sonar for target location, a narrow beam echo sounder, a pressure gauge for depth determination*, a Savonius rotor for measuring the speed of water flowing past the hull, and an external thermistor probe (borrowed from DSRV Alvin) for measuring its temperature.

Dive sites in Guaymas Basin were selected using Sharman's (1976) detailed bathymetric chart and 3.5 kHz profiles from Scripps Institution's 1972 HYPOGENE Expedition, and located with Maxine D's 12 kHz echo-sounder, radar and satellite navigation system. Radar ranges taken at the launch and recovery postions fix the end points of each Seacliff dive, with a positioning error that may be as great as 1 km for some sites. Determination of the submersible's track over the sea floor was by dead reckoning using the boat's gyro and the ambiguous speed data from its Savonius rotor. Regular directional acoustic ranging between Seacliff and Maxine D did not provide a useful input to this dead reckoning, because of imprecision of the ranging system and uncertainty of the ship's position.

Average length of time on the sea floor was 4.2 hours, with an additional 3-4 hours per dive spent descending and ascending. Most of the bottom time was devoted to cruising close to the sea floor (usually within 1 m) at a speed of about 1 km/hr, taking photographs at frequent intervals. When rock outcrops were encountered, attempts were made to land Seacliff on adjacent level mud, and to collect samples. Except on steep scarps, lithified outcrops were rare interruptions on a generally muddy sea bed: several times apparently coherent masses of sedimentary rock disintegrated in the jaws of the manipulators, or after they had been placed in the collecting basket. Collecting rock specimens from the floor of Guaymas Basin was greatly hampered by the ubiquitous presence of a loose, organic-rich veneer of flocculated sediment, which was swept into suspension by the submarine's prop wash. In the general absence of appreciable bottom currents, these "dust clouds" took up to an hour to disperse; the lack of visibility frustrated attempts at reversing course to return to particular rock outcrops that the observer had noticed as Seacliff passed by, and prevented use of the manipulators for 15-100 minutes after the boat had landed.

Between dives, 12-15 hour hiatuses were required for recharge of Seacliff's batteries and check out of its systems. Some of these periods were used to gather bathymetric data around potential dive sites, but only to a limited extent because

* All depths quoted in this report are as measured by this instrument.

of the availability of dense, high-quality data from previous surveys, the frequent poor functioning of Maxine D's echo sounder, and other heavy demands on the time of the two-man scientific parties.

DIVE SUMMARIES

The axial rift

Dive 305, observer P. Lonsdale, was onto the peak mapped by Sharman (1976) and Lawver and Williams (in press) within the northern trough, near its intersection with the northeastern margin of the basin. It seemed a likely candidate for basalt outcrops, though earlier dredging had recovered only mud. Also, the location of the site near the principal source of terrigenous sediment influx made it a critical test of whether Guaymas Basin bottom waters would be too murky for effective submersible work.

Seacliff landed at a depth of 1830 m on the southeast flank of the peak, a sediment covered slope inclined at 15°. The diatomaceous sediment was light colored, but except where it had been exposed in large biogenic mounds and burrows it was veneered with a darker, greenish layer of loose organic debris. The bottom water was very turbid, especially after the surface sediment had been put into suspension by the boat's prop wash; this hampered photography, except on steep scarps, but did not prevent visual observation. Seacliff proceeded upslope to a 12 m-high near-vertical fault scarp, which exposed semi-lithified white diatomaceous ooze intercalated with darker clastic layers a few centimeters thick. The next 1.5 hours of the dive were spent photographing the fault scarps on the southeast side of the "peak", and mapping them with the aid of the CTFM sonar (Fig. 3a). The principal fault scarps were oriented 035°, parallel to the trough walls and at right angles to the predicted direction of Pacific-North America plate motion. However they were intersected by minor normal faults that were well displayed as offsets in the horizontal laminated strata outcropping on the scarp faces, and by two major fault scarps, oriented at 305°, which defined the southwest margins of the "peak". The fault scarps were 8-20 m high near-vertical steps on sedimented slopes with an average inclination of 20-30°, and appeared very fresh, with only minor differential weathering of the various lithologies exposed. There was no talus at their feet. The top of the highest scarp, the summit of the "peak", was a sensibly flat plateau at a depth of 1805-1810 m, that was slightly tilted toward the northwest. The last hour of the dive was spent crossing this plateau, and driving toward the northwest wall of the trough (Fig. 3a). The northwest flank of the peak, now known to be flat-topped ridge, was much gentler than its southeast flank, with only a single steep 8 m scarp.

The principal conclusion from the dive was that this peak, the largest of several that occur within the northern rift valley, was an asymmetric horst, rather than a volcanic ridge. Its pattern of orthogonally intersecting faults is appropriate for regional northwest-southeast tension in a thick lens of sediment. The freshness of the fault scarps despite the rapid rate of sediment accumulation indicates recent and probably continuing tectonic activity.

Dive 306, observer L. A. Lawver, was onto the peak mapped by Sharman (1976) in the center of the southern trough. On surface-ship records this feature appeared similar to the ridge explored on Dive 305; its steepest slope was to the southwest, and the dive began on this flank.

Seacliff landed at 1780 m beside a straight fault scarp that was oriented about 320°. Sedimentary strata similar to those seen on Dive 305 outcropped on this scarp, and some of the white interbeds were only 1-2 cm thick. The submersible climbed up this scarp, taking photographs in water that was much clearer than on Dive 305, and had a southeasterly current that rapidly dispersed the sediment cloud. Above a 15 m-high near-vertical section was a 15 m-high bevel, inclined at about 45°, that had a sediment cover and no outcropping differentially weathered strata. The top of the slope, at 1750 m, was a flat pleateau, which Seacliff travelled northwestward across for about 250 m before turning to go back down the southwest slope of the peak. This slope dropped relatively steeply (about 30°) to 1825 m, but without any scarps like the one encountered along strike (Fig. 3b). The slope gradually leveled off, and the submersible continued southwest along the floor of the southern trough for another 2 hours to the vicinity of the high heat flow "major geothermal anomaly" reported by Lawver et al. (1975). Along the entire track the sea floor was heavily burrowed sediment, with large biogenic mounds. Near the end of the dive, at a depth of 1870 m, some large (1 m-wide) craters bordered by 1 m-high mounds were inspected carefully, in case they were hydrothermal vents. It was concluded that they were biological in origin, perhaps made by some large fish or octupus; several large octupus had been encountered during the dive.

It is clear that the "peak" in the southern axial rift valley is also a flat-topped horst, like that examined in the

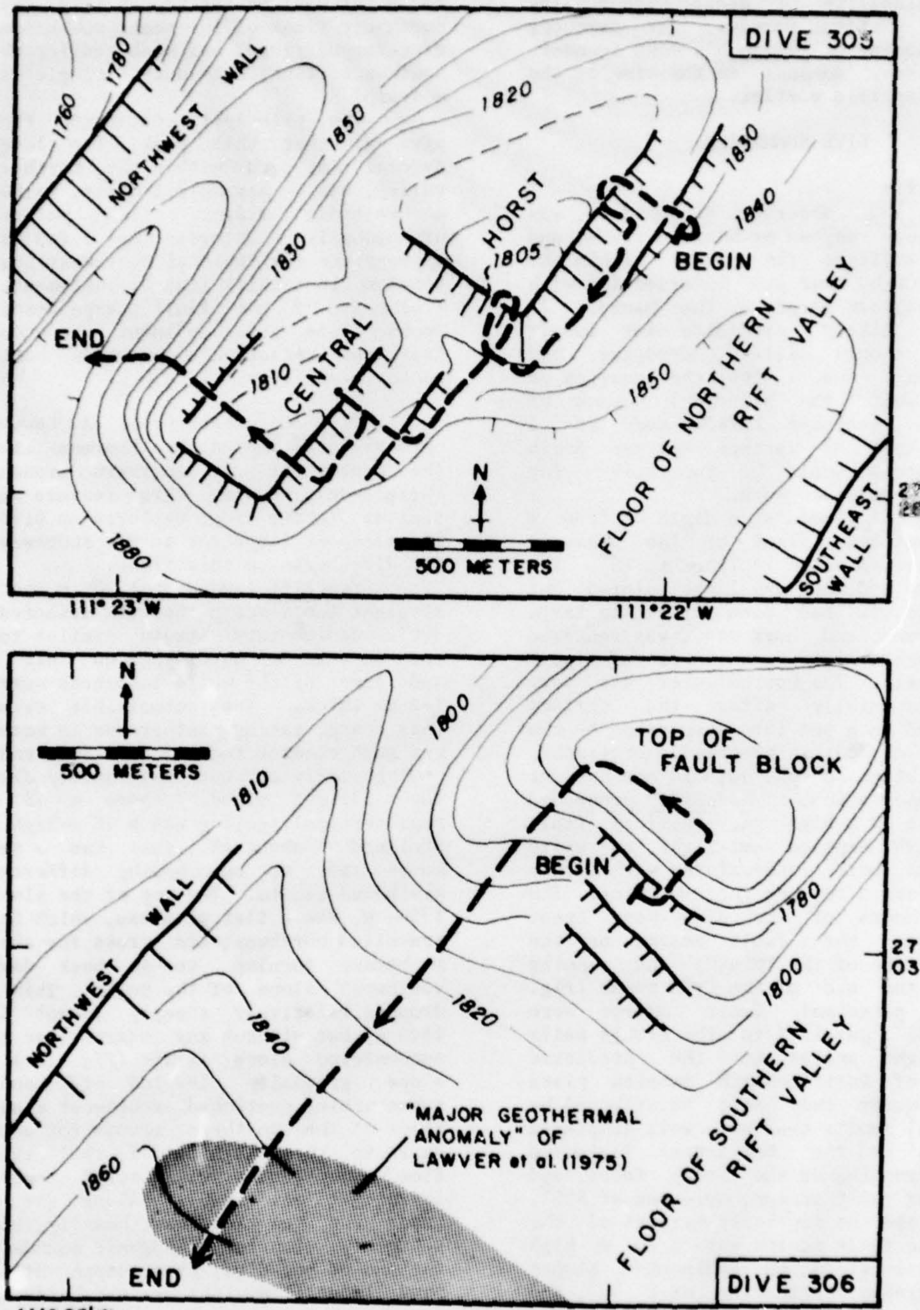

Fig. 3. Sketch map of the sites of Dive 305 (in the northern rift valley) and Dive 306 (in the southern rift valley). Fault scarps are shown schematically. Depths are as measured by Seacliff's pressure gauge; isobaths beyond range of the submersible's sonars are based on echo-sounding charts (Sharman, 1976), with the depths adjusted to correspond to Seacliff's measurements. Latitudes and longitudes are approximate.

northern trough on Dive 305, though its side slopes appear on surface-ship records to be generally less steep, with steep fault scarps exposed only on the southwest flank. We saw no surface manifestations of the locus of high heat flow in the southern trough.

Dive 308, observer P. Lonsdale, was into the northern axial rift valley near 27°18'N. Most of the trough has a smooth floor, and on 3.5 kHz records it can be seen that this results from burial of tectonic relief by acoustically transparent layers of young flat-lying sediment. We had examined terrain of this type towards the ends of Dives 305 and 306, and found little of interest. For a length of 2-3 kilometers around 27°18'N the trough floor shoals, and rises above the surrounding ponds of transparent sediment with hyperbolic echoes indicative of small-scale roughness. On seismic reflection profiles across this segment, volcanic basement lies at least 250 m below the central part of the valley floor, but seems to almost crop out near the foot of the northeast wall (though the records are difficult to interpret because of confusing side-echoes). Our plan for this dive was to land just outside the trough (to ensure a safe bottom approach and provide a reference point to dead reckon from); to proceed down the northwest wall into the rift valley floor to discover the nature of the small-scale roughness and to search for basement outcrops or hydrothermal phenomena; and to terminate the dive by ascending the northwest wall.

Seacliff approached the bottom (1745 m) about 150 m northwest of the brink of the wall, and rather than landing went southeast at a depth of 1675 m, collected a narrow-beam echo-sounding record of the steep (average 50°) scarp, and landed on flat, muddy sea floor about 50 m beyond the foot of the scarp, at a depth of 1863 m (Fig. 2, inset). The temptation to examine the wall right away was irresistible, so we moved toward it, climbed a 25 m wide 30° talus slope, and set down again facing the foot of the scarp. The talus slope was made of white diatom ooze boulders and pebbles, but attempts to sample them were thwarted by their lack of coherence. Seacliff then climbed 30 m up the wall, taking photographs: the scarp was almost a

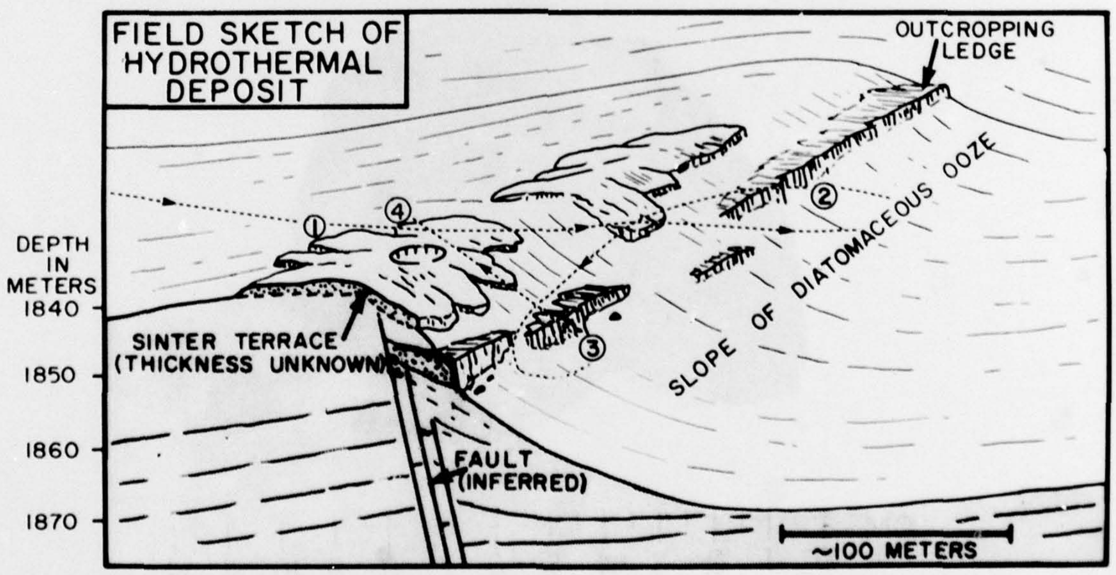

Fig. 4. Sketch of the hydrothermal deposits examined on Dive 308, relying on information from Seacliff's CTFM sonar, pressure gauge, and cameras, and on visual observations. Submersible track (simplified) shown by dotted line. Numbers are landing sites where we attempted to sample. Photo in Fig. 5 is from site 1; sample is from site 3. View is to north.

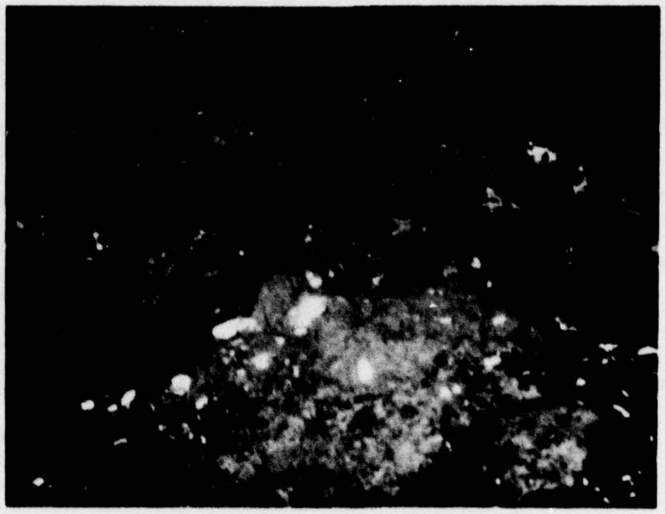

Fig. 5a. Bottom photo taken with Seacliff's 70 mm camera on Dive 308 shows 1 m-high scarp at northwest edge of hydrothermal deposit (Site 1 of Fig. 4). Note dark (ferromanganese-covered) rock, and abundant white valve of dead molluscs.

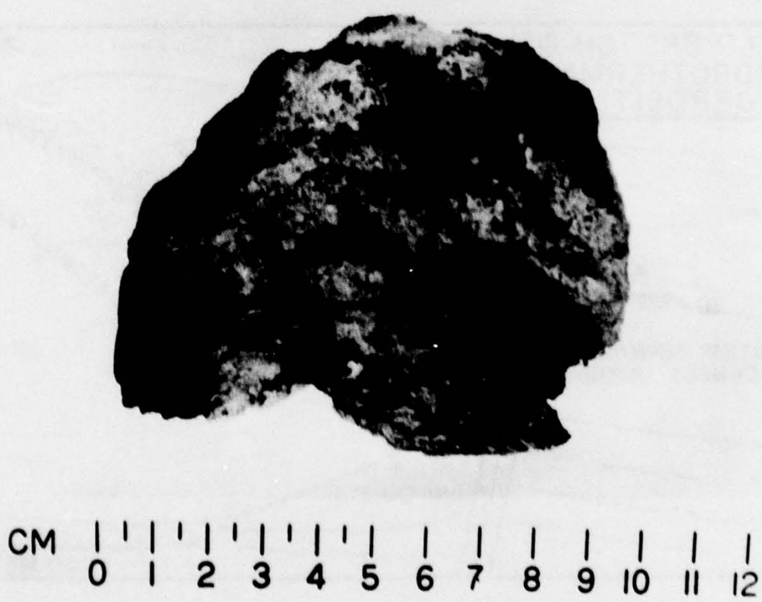

Fig. 5b. Part of the sample recovered from the hydrothermal deposit. Small part of dark exterior shows at left edge. Most of interior is white, fibrous talc with patches of green smectite (grey in photo) and pyrrhotite crystals (black speckles in photo).

continuous slope, with a few minor benches, developed in a massive white rock. There were some patches of soft boulders on gentler parts of the scarp, but little sign of internal stratification. After climbing about a third of the way up the wall, we reversed course, and landed back at its foot. We then proceeded south over hummocky, sediment-covered terrain, crossing a steep (45^{o}) sediment-covered slope that dropped 5 m to the southeast (assumed to mark the trace of a minor fault near the foot of the principal scarp). After travelling 250 m Seacliff changed course left to examine a faint CTFM target. Climbing a gentle slope on the approach to this target we first noticed that white valves of dead clams were strewn over the sea floor, and they rapidly increased in density to form an almost continuous carpet. Seacliff landed at the CTFM target, which was an outcrop of brown, apparently sedimentary, rock near the top of the slope (Fig. 5a). There were no loose fragments that the manipulators could pick up, and because the CTFM showed that we were at the margin of a rather extensive outcrop we moved on to look for better sampling sites. The outcrop covered the crest of the slope (Fig. 4), and was exposed as ledges on a steep southeast facing (fault ?) scarp which was oriented about 320^{o}, approximately parallel to the nearby wall of the trough. After several attempts to sample by pulling joint blocks off the ledges, attempts that were in vain because the friable rock was crushed by the manipulator jaws, we succeeded in prying loose a 20 cm^3 block and dropping it intact into the sampling basket. Although the external surface was dark brown, the unexposed interior of the rock was predominantly white (Fig. 5b). The sample was from the 5 m-high vertical face of a ledge that outcropped along the scarp at a depth of 1853 m. We then climbed the scarp and the overlying 30^{o} slope (all strewn with dead clam shells) to the crest of the ridge (1837 m), where we tried to land at a 5 m-wide 1 m-deep crater, which had a vertical circular wall of the white, brown-encrusted rock, was filled with a continuous cover of dead clams, and looked like a vent for hydrothermal discharge. After waiting for an hour for our sediment cloud to clear, we discovered that we had landed just out of range of this target, and were unable to sample it or to probe with the thermistor on the manipulator arm. (The thermistor had been operating rather erratically throughout this and the previous dives, and because of the tendency for its electronics to overheat, it was only switched on for periods of half an hour at a time; it never sensed any temperature anomalies attributable to hydrothermal activity). Because the bottom water in the immediate vicnity of these outcrops had by now been made excessively turbid by our maneuvering, we spent the remaining 45 min of bottom time moving at 1 km/hr on various courses and speeds in search of other CTFM targets nearer the center of the rift valley: we found only hummocky, sediment-covered terrain, and no lithified outcrops.

The rock sample recovered on Dive 308 was a hydrothermal sinter with a porous, earthy texture. Chemical, mineralogical and isotopic analysis is presently in progress. Preliminary findings are that most of the sample is composed of well-crystallized authigenic talc, a hydrated magnesium silicate. In veins throughout this soft material, and in large scattered crystals, is the iron sulfide mineral pyrrhotite, with subsidiary amounts of copper and zinc sulfides. The pyrrhotite crystals are euhedral hexagonal platelets, similar to those produced in sea-water/basalt hydrothermal experiments by Hajash (1975). Masses of authigenic montmorillonite also occur, and the brown outer crust is a thin patina of ferromanganese oxide and calcium phosphate. The deposit is a precipitate formed where hot mineralized hydrothermal fluids have encountered cold sea water; the clustering of molluscs is similar to that found around active hydrothermal vents at other spreading centers (Lonsdale, 1977). Transition metals in the precipitate are probably derived from the underlying igneous rocks, magnesium from sea water, and silica mainly from the surrounding diatomaceous sediments. The significance of the sample is threefold. It is hard evidence for recent discharge of hydrothermal fluids through the floor of the axial rift valley, and hence evidence that part of the lithospheric cooling there is by "open system" convection. It is the first reported occurrence of in situ authigenic talc in the deep-sea, though this mineral is a common product of sea-water/basalt hydrothermal experiments (e.g., Hajash, 1977), hydrothermal formation of magnesium silicates has been suggested as an important control of the geochemical balance of ocean magnesium (e.g., Drever, 1974), and the allied mineral sepiolite has been dredged several times from likely sites of hydrothermal discharge (e.g., Bowles et al., 1971). It is the first sample of authigenic metal sulfides that are precipitating at the sea floor to form a modern deposit similar to the ancient volcanogenic massive sulfide deposits, which are major sources of copper, zinc, and lead ores (e.g., Hutchinson, 1973); though the Guaymas Basin sulfides may be of no commerical value because of their inaccessiblity, their study will help

explain the genesis of this class of ores, and may aid prospecting and exploitation elsewhere.

In addition to the important discovery and sampling of the hydrothermal deposit, and the crude mapping of its extent and relationship to structure (Fig. 4), Dive 308's contributions included establishing that the wall of the axial rift valley is in places a single steep scarp, apparently formed by a normal fault with over 100 m of throw that cuts semi-lithified, massive, diatomaceous ooze, and that the roughness on the valley floor is caused mainly by motion on subsidiary, parallel faults.

Dive 309, observer L. A. Lawver, was also into the northern trough, in the vicinity of Dive 308, and the strategy followed was the same as for that dive (Fig. 2, inset). The initial descent aimed about 1 km south of Dive 308, to see if hydrothermal sinters occurred on the even rougher valley floor there; if not, we hoped to relocate and reexamine the sampled deposit, by returning northward along the valley.

Seacliff approached the sea floor near the top of the cliff, drove southeast, and landed in the rift valley at its foot. It proceeded south, over sediment-covered hummocky terrain (perhaps formed by sediment smoothing of an orthogonal pattern of fault scarps), and obliquely crossed a 10 m-high southeast-facing fault scarp. Seacliff travelled on 160° for about 800 m, then changed course to 020°; after about 900 m on this new heading, and a total of almost 2 hours spent on the rift valley floor, no hydrothermal deposits had been located, and the submersible turned northwest to examine the wall of the trough. A small scarp with outcropping ledges of white rock (probably diatomite) was encountered near the foot of the wall, but the rock was too friable to keep in the sample basket. Just beyond this was a short talus slope with soft boulders of diatomaceous ooze, up to 1 m in diameter, and a cliff which rose almost vertically for 30 m. The rocks exposed on this part of the trough wall were not the massive diatomites seen nearby on Dive 308, but were thinly bedded, with 10 cm-thick white strata alternating with 40 cm-thick brown layers. The strata were steeply tilted, dipping about 45° towards the southwest. At the top of this vertical cliff was a 30° bevel, covered with sediment and without outcropping ledges. At about 1765 m this flattened out, and after travelling a few tens of meters over this flat sea floor, the dive was terminated.

It is difficult to determine precisely the track of Dive 309, relative to Dive 308. The attempt in the inset of Fig. 2 relies heavily on radar fixes (of fairly poor quality this far from land) at the launch and recovery sites. The absence of sinter terraces along the Dive 309 track, which must have passed within 100-200 m of those sampled the day before, may indicate that they are of very limited extent, and that their discovery on Dive 308 was a fortunate accident. However, after Dive 309 concern was expressed that the CTFM sonar had not been operated in its most efficient mode; the effective range of this sonar, which is crucial for locating rock outcrops in generally sedimented terrain, may have been less than 50 m on either side of Dive 309's track, rather than the 250-300 m useful range on Dive 308. The area searched may have been correspondingly reduced. Dive 309 did cross a steep slope that is plausibly the along-strike extension of the sinter-covered fault scarp of Dive 308 (Fig. 2, inset), but it was completely buried in sediment.

Dive 309 provided another look at the wall of the northern trough. The layered sediments were evidently stratigraphically higher than the massive section explored on Dive 308, since they were dipping steeply to the southwest. The steep tilt is further evidence for significant faulting within the sediment prism at approximately right angles to the principal faults which are parallel to the spreading axis. On both dives the wall appeared to be mainly a single fault scarp, rather than a complex step-faulted structure, and to be relatively fresh; there was scant evidence of significant scarp retreat except in the softer, young sediments bevelled off at the top of the scarp. Reichle (1975) located a swarm of shallow earthquakes on this wall, about 2 km southwest of the dive sites (Fig. 2).

The southeast transform fault

Dive 302, observer P. Lonsdale, was onto the transform fault zone that connects the spreading axis in the southern trough of Guaymas Basin to the axis in Carmen Basin. This was chosen as a site to look for young tranform fault structures, and for possible volcanic extrusions and hydrothermal discharge along the fault zone, because it has a slower rate of sediment burial than the northwest transform, which runs along the prograding Sonoran slope, and because it was the site of a large recent earthquake (magnitude 6.3 on 31 May 1974; Reichle, 1975). The plan was to land near the edge of the basin floor, at a depth on Sharman's (1976) chart of 1900 m, to examine the shallow groove at the foot of the basin slope (considered to be the most likely place to observe transform fault neotectonics), and then climb up the basin margin (i.e., the continental slope of Baja

California). The plan went awry because of the lack of an echo sounder aboard Maxine D at the time.

Seacliff landed at a depth of 1765 m, on a gentle (10°) muddy slope inclined to the northeast. We reasoned that we were part-way up the continental slope, and turned onto a heading of 030° to move towards its foot. However, after travelling only a few meters the slope flattened out, at a depth of 1775 m, and thereafter our northeasterly heading took us slowly upslope. There were three possible explanations for the 125 m difference between the anticipated and actual maximum depth: an error in Sharman's (1976) chart; a mislocation of the dive site; and a discrepancy between the depth calculated by echo sounding and the depth measured by Seacliff's depth gauge. The first seemed unlikely because of the good bathymetric control for the chart; the second seemed plausible in view of the difficulties of radar navigation in Guaymas Basin (where many of the coasts are mislocated on charts); the third turned out to be true. Before we were sure of this, and certain that we were not merely on a shallow step on the continental margin, we had travelled about a kilometer from the foot of the slope, and we decided to press on across the basin floor.

Throughout the 4 kilometers traversed during the 3.5 hours of bottom time we encountered only gentle sediment slopes, with no scarps, fissures or other evidence of tectonic activity, and no evidence of volcanic or hydrothermal activity. The sea floor had a very dense carpet of brittle stars, commonly more than 1 per square meter, and abundant large white starfish. We took about 350 70 mm pictures, over 200 35 mm pictures, and two rolls of movie film of these and other animal life.

Dive 310, observer P. Lonsdale, was planned to extend Dive 302's traverse of the transform fault zone to the southwest, up the continental slope. The absence of surface indicators of transform tectonics on the earlier dive might have been because the presently active strike-slip faults are on the slope.

With an operational echo sounder on Maxine D we had no difficulty in positioning Seacliff into the marginal depression, about 200 m from the foot of the slope at a depth of 1767 m. The sea bed was as observed during Dive 302, muddy with dense brittle stars. As we travelled southwest, the sea floor gradually shoaled with a steepening concave slope to a depth of 1735 m. There was no sign of recent tectonic activity. The slope then steepened to about 30°; it remained sediment-covered with no outcropping ledges, and differed from the young fault scarps elsewhere in the basin in being deeply indented, rather than straight. Several tripod fish were noticed, systematically facing southeast, indicative of a bottom current along the slope from that direction. Above 1650 m, signs of current activity diminished, the slope flattened to form a terrace on the lower continental slope, and we encountered extensive outcrops of sedimentary rock. The rock was in large tabular slabs, several meters across and commonly 1-3 m thick, that were lying with slight tilts on the sediment surface. Most of the tops of the slabs were buried in sediment, but on their exposed edges stratification was visible, and the lithology appeared to be brown siltstone and sandstone. Several attempts to sample were thwarted by the thick dust cloud that persisted for a long time after landing. We travelled along the slope at 1625 m for several hundred meters over large isolated rock fragments, covering about 10% of the sea floor, which appeared to be glide blocks that had moved downhill from an outcrop. After stopping on the bottom at another potential sampling site for 90 minutes, waiting in vain for suspended mud to clear, we unsuccessfully attempted to grab rocks with the manipulators while Seacliff was still moving ahead of its sediment cloud. Two and a half hours after we first arrived at the field of rocks we resumed our southwesterly course upslope, and climbed a steep (50-60°) scarp that truncated subhorizontal ledges of in situ sedimentary rock. At the top of this scarp, still on the lower part of the continental slope at 1540 m, we terminated the dive.

We concluded from Dives 302 and 310 that any surface traces of strike slip or accessory oblique normal faulting, which are preserved as small sediment scarplets at other oceanic transform fault zones (e.g., Eittreim and Ewing, 1975; Lonsdale, in press), are rapidly erased in Guaymas Basin. Perhaps the rate of sediment burial is merely faster there, or perhaps the dense cover of mobile brittle stars that are continually tilling the surface sediment rapidly smooth any small-scale irregularities. In any event, the lack of evidence for tectonic deformation in the surface sediments above the central transform fault zone, connecting Guaymas Basin's two axial troughs (Fig. 2), which has been cited as a reason for doubting the existence of transform motion there (Bischoff and Henyey, 1974), no longer seems anomalous. Although the sedimentary rocks that outcrop 150-200 m above the foot of the continental slope were not sampled, they visually resembled the siltstone of Miocene or early Pliocene age that Moore

(1973) dredged from the northeast margin of the basin. Seismic reflection profiles along the dive traverse show truncation of deep sedimentary layers by this part of the lower slope. These siltstones are believed to have been deposited in a basin, the "proto-gulf" that existed before the present episode of sea-floor spreading, and the scarp on which they are exposed is probably a fault scarp inherited from the initial opening of the basin. Continuing high seismicity on or near this fault scarp may be responsible for rockfalls that give the scarp its relatively fresh appearance, and produce the abundant large talus blocks that have slid down gentle slopes for over 100 m from the scarp face. The recency of such rockfalls is demonstrated by the lack of burial of these large slabs.

The submerged flank of Tortuga volcano

Dive 303, observer S. Bloomer, started within 3 km of the south coast of the island, close enough that the launch site was sheltered from the waves, and close enough for confidence that we were still on the steep insular slope, though Maxine D lacked a working echo sounder.

Seacliff landed at a depth of 830 m on a 10° sediment-covered slope, and moved downslope away from the island. A basalt outcrop that extended downslope between 970 m and 983 m had broken pillows on a near-vertical west-facing scarp that was about 6 m high. After about an hour the submersible turned east, and moved approximately along the 1050 m contour towards a steep scarp that had been mapped by Batiza (in press). About 1 km of sediment-covered sea floor, lacking rock outcrops, was traversed before arriving at some small patches of pillow basalt, partly buried by sediment. Seacliff stopped for 20 mins and attempted to sample, but there were no loose fragments, so it moved off toward a large basalt scarp that trended northeast-southwest, down to the southeast. After running along the top of this scarp, the submersible went down its face for about 30 m to 1100 m; the inclination was about 40°, and tubular lava dusted with sediment extended downslope. The scarp is approximately aligned with and parallel to the large fault inferred to truncate the "older series" lavas at the southeast end of Isla Tortuga (Batiza, in press). The observation of fresh lava tubes extending downslope demonstrates that if it was initiated as a fault scarp, then it has been smothered by "younger series" lavas. The remainder of the dive was spent exploring and photographing the young volcanic forms on this scarp. The dive was terminated prematurely, before loose rocks suitable for sampling could be located, by failure of the main hydraulic pump.

Dive 304, observer P. Lonsdale, had the advantage of an operational echo sounder for positioning the launch, but seas were still rough enough to hamper safe recovery of the submersible in exposed sites. The strategy was to start the dive near the foot of the insular slope, and to move upslope toward the island and into increasingly sheltered water.

Seacliff landed on a flat bottom at 1280 m, in a valley between the Tortuga edifice and an older, ancestral volcano mapped and dredged by Batiza (in press). The sea bed was light-colored mud, densely covered with brittle stars. We travelled on 340°, a course maintained throughout the dive, in part because the CTFM sonar was malfunctioning, and therefore revealed no targets off to the side of our track. Within 15 m we came to the abrupt foot of the 10°-15° insular slope, which lacked brittle stars. We proceeded upslope, photographing a steep face of pillow basalt that outcropped from 1202 m-1215 m, and stopped at a similar outcrop near 1160 m. The pillow and tubular basalt here appeared very fresh, with well preserved surface corrugations that formed during cooling (Moore, 1975). A sample was collected from the talus at the foot of this low flow front. Beyond this outcrop, the sediment-covered slope was densely populated with large holuthuria, an isolated basalt boulder completely encircled by a scour moat (indicative of variable bottom currents) was passed at 1101 m, and we stopped at another small outcrop of tubular basalt near 1030 m. The climb up the slope, and the dive, was terminated at 992 m.

A surprising feature of both dives was the scarcity of rock outcrops on the south flank of this young volcanic island, which is presently in the fumarolic stage of activity and has a frozen lava lake of very recent appearance within its caldera. The only basalt outcrops that had not been buried by rapid sedimentation were exposures of steep flow fronts, and these may have been kept sediment-free by tidal currents, for there was widespread evidence of current activity (dense colonies of filter feeding animals on the rocks, frequent tripod fish, and some shallow scour marks). The lavas we saw probably resulted from submarine flank eruptions, rather than from extension of subaerial flows into deep water. Detailed chemical analysis of the recovered sample, and comparison with subaerial rocks from the island, should give further information of the flows' relative age and provenance; this study is presently being carried out by R. Batiza. The lavas certainly cooled in deep water, producing photogenic forms similar to

those at mid-ocean spreading centers (e.g., Ballard and Moore, 1977).

SUMMARY OF PRELIMINARY RESULTS

Observations during dives into the northern and southern trough of Guaymas Basin demonstrated that these are rift valleys with a style and pattern of recent faulting that is appropriate for the predicted direction of Pacific-North America plate motion. Close-up examination of impermanent, and therefore young, fault scarps in friable sediments helps bridge the gap between seismicity studies, which monitor instantaneous plate motions, and magnetic anomaly studies, which have proved ineffective in recording long-term plate motion in the Gulf, except by extrapolation from anomaly sequences at the mouth. The wall of the northern trough, within 1-2 km of the valley axis, exposes semi-lithified and mainly pelagic sediment with a stratigraphic thickness of at least 100 m, implying that the present grabens have recently opened in relatively old crust, rather than being steady-state features. Large ridges and small-scale roughness of the valley floor were created not by volcanism but by an orthogonal pattern of normal faulting, with the primary fault system parallel to the spreading axes. We encountered no basalt in the valley, and think it likely that magma rises to the sea floor very rarely, if ever; if it does the lava is rapidly buried with sediment. Hydrothermal fluids do discharge in the rift valley floor, venting through the siliceous sediments along normal faults. These discharges provide evidence of the hot, underlying intrusions, and transport dissolved ions derived from them; at the sea floor these ions and others derived from sea water and the sediments are precipitated as consolidated sinter deposits of hydrothermal talc, metal sulfides, and smectite. The discovery of recent sea-floor venting of a hydrothermal system helps explain the pattern and magnitude of the conductive flux which has been measured by intensive heat flow studies, and the anomalous helium isotope ratios measured in the bottom water.

Neotectonic observations at a seismically active transform fault zone were more difficult, presumably because the lower fault scarps created by strike-slip faulting are so rapidly erased. The principal geomorphic effect of this style of faulting in Guaymas Basin may be to engender rock falls and slides from the continental margins. There was no sign of "leaky transform fault" volcanism or hydrothermal activity.

On the south flank of Tortuga volcano, at depths of 830 m-1280 m, some steep fronts of submarine lava flows outcropped through the sediment, but exposures were surprisingly rare. There was no evidence of post-eruptive faulting, though fault scarps are common on the island.

An important result of any oceanographic field program, and one test of the significance of its observations, is the way in which it modifies or stimulates future work at sea. Scripps Institution of Oceanography is operating a seismic profiling, sampling and heat flow cruise in Guaymas Basin in February 1978, and the vessel's proposed track and the planned locations of piston cores, deep hydrocasts and intensive heat-flow studies are being modified to exploit our discovery of hydrothermal deposits in the northern rift valley. In late 1978 the Deep Sea Drilling Project ship D/V Glomar Challenger is scheduled to drill in Guaymas Basin, with geothermal studies of the oceanic crust as one objective, and interest has been expressed in positioning a drill site in or near the sinter terraces. When our descriptions of these deposits and the sulfide minerals they contain are published, we expect them to stimulate an interest among economic geologists in modern hydrothermal systems on the deep-sea floor, as did the first descriptions of sulfide muds in the Red Sea. Finally, we are already considering plans for a return to the Guaymas Basin axial rift valley and hydrothermal site for a more thorough near-bottom study.

Acknowledgements

Although this report was prepared by the chief scientist of the Gulf of California expedition it obviously relies on the observations, photographs and tape-recorded narratives of the other diving observers, L. A. Lawver and S. Bloomer. The efforts and stoicism of would-be observers D. Fornari and R. Batiza are also appreciated. A greater debt is owed to the officers and crews of DSV-4 Seacliff and M/V Maxine D, especially to the boat's commanding officer, Lt. C. Gragg, and the ship's captain, Mr. A. Paulk, for their skill and enthusiasm, above and beneath the waves. Many people who stayed ashore at Submarine Development Group One and the Scripps Institution of Oceanography were also instrumental to the success of the expedition. Special thanks to K. Poole for driving at night and high speed through the Sonoran Desert to deliver a replacement transducer, without which dives in the rift valleys of Guaymas Basin would have been impossible.

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SUBMERSIBLE EXPLORATION OF GUAYMAS BASIN: A PRELIMINARY REPORT OF THE GULF OF CALIFORNIA 1977 OPERATIONS OF DSV-4 Seacliff by Peter Lonsdale, University of California, San Diego, Marine Physical Laboratory of the Scripps Institution of Oceanography, La Jolla, California, 92093. SIO Reference 78-1, 20 January 1978.

A diving program with DSV-4 Seacliff examined the submarine geology of Guaymas Basin, a young and growing basin in the Gulf of California. Four dives in the axial rift valleys allowed observation of fresh normal fault scarps that were oriented parallel and orthogonal to the direction of relative plate motion; established that the major peaks within the axial rift valleys were sedimentary horsts and discovered and sampled extensive sinter terraces of talc and metal sulfides, built around hydrothermal vents. Two dives across the southeast transform fault found no fresh fault scarps on sediment slopes that were efficiently tilled by a very dense benthic fauna, but encountered extensive ledges of clastic rocks that are believed to be outcrops of old "protogulf" sediments. Two dives on the insular slope of Isla Tortuga photographed and sampled flow fronts of fresh pillow basalt that mark submarine flank eruptions.

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SUBMERSIBLE EXPLORATION OF GUAYMAS BASIN: A PRELIMINARY REPORT OF THE GULF OF CALIFORNIA 1977 OPERATIONS OF DSV-4 Seacliff by Peter Lonsdale, University of California, San Diego, Marine Physical Laboratory of the Scripps Institution of Oceanography, La Jolla, California, 92093. SIO Reference 78-1, 20 January 1978.

A diving program with DSV-4 Seacliff examined the submarine geology of Guaymas Basin, a young and growing basin in the Gulf of California. Four dives in the axial rift valleys allowed observation of fresh normal fault scarps that were oriented parallel and orthogonal to the direction of relative plate motion; established that the major peaks within the axial rift valleys were sedimentary horsts and discovered and sampled extensive sinter terraces of talc and metal sulfides, built around hydrothermal vents. Two dives across the southeast transform fault found no fresh fault scarps on sediment slopes that were efficiently tilled by a very dense benthic fauna, but encountered extensive ledges of clastic rocks that are believed to be outcrops of old "protogulf" sediments. Two dives on the insular slope of Isla Tortuga photographed and sampled flow fronts of fresh pillow basalt that mark submarine flank eruptions.

Vb. Marine Geology

1. Peter Lonsdale

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